Answering the *Spitzer* white paper call to open new proposal opportunities*

A search for rocky planets transiting brown dwarfs

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Exoplanetary science has reached a historic moment. The *James Webb Space Telescope* will be capable of probing the atmospheres of rocky planets, and perhaps even search for biologically produced gases. However this is contingent on identifying suitable targets before the end of the mission. A race therefore, is on, to find transiting planets with the most favorable properties, in time for the launch.

Here, we describe a realistic opportunity to discover extremely favorable targets – rocky planets transiting nearby brown dwarfs – using the *Spitzer Space Telescope* as a survey instrument. Harnessing the continuous time coverage and the exquisite precision of *Spitzer* in a 5,400 hour campaign monitoring nearby brown dwarfs, we will detect a handful of planetary systems with planets as small as Mars. The survey we envision is a logical extension of the immense progress that has been realized in the field of exoplanets and a natural outcome of the exploration of the solar neighborhood to map where the nearest habitable rocky planets are located (as advocated by the 2010 Decadal Survey). Our program represents an essential step towards the atmospheric characterization of terrestrial planets and carries the compelling promise of studying the concept of *habitability* beyond Earth-like conditions. In addition, our photometric monitoring will provide invaluable observations of a large sample of nearby brown dwarfs situated close to the M/L transition. This is why, we also advocate an immediate public release of the survey data, to guarantee rapid progress on the planet search and provide a treasure trove of data for brown dwarf science.

a characterizable rocky exoplanet to turn JWST to

The study of exo-atmospheres is a fascinating and fast growing field, so far mostly restricted to close-in gas giants (Seager & Deming 2010). We propose to extend this highly important field to terrestrial planet atmospheres. It is now widely recognized that M dwarf stars are attractive targets because of their small sizes, and consequently reduced size contrast between planet and star. Even so, observing the atmospheres of any Earth-sized transiting planets around M dwarfs may be difficult with *JWST*. Belu et al. (2011) calculated the expected signal to noise and the necessary photometric precision associated with the detection of atmospheric features via transmission and reflection spectroscopy using MIRI (on board *JWST*). Reaching a 5σ detection of spectral features in the atmosphere of a rocky planet in the habitable zone of an M dwarf will require co-adding together almost every single occultation and transit occurring during *JWST*'s entire lifetime.

We extended this work in the context of brown dwarf primaries who present more favorable characteristics for the detection but also for the future characterization of rocky exoplanets (see Fig. 1). When wishing to detect photons emitted by an exo-atmosphere (at occultation), the distance of that exoplanet relative to the Solar System is what primarily matters. In addition, for a given planetary equilibrium temperature, the contrast between the central object and the planet is highest and most favorable, the fainter the primary. This makes brown dwarfs natural targets to consider; they possess other advantages:

- for a given planetary equilibrium temperature, the orbit gets shorter with decreasing primary mass, increasing the probability of transit and providing 50+ occultations per year (and 50+ transits) (Fig. 1);
- the planet to brown dwarf size ratio means transiting rocky planets produce deep transits and permit the detection of planets down to Mars' size in a single transit event when using *Spitzer* (Fig. 2);
- the reliability of the detection is helped by the absence of known false astrophysical positives: brown dwarfs have very peculiar colors, small sizes, and being nearby, have a high proper motion allowing to check what is within their glare.

Brown dwarfs older than ~ 0.5 Gyr have a near constant radius over their mass range: a fairly accurate estimation of the size of the planet can be obtained without requiring a complete characterization of the host as when we search for transits on solar-like stars.

Observing in broad band would reveal the presence of an atmosphere through the phase curve (Maurin et al. 2012). Using narrow bands can provide spectral signatures (Selsis et al. 2011). The amplitude of the phase curve of a planet in the habitable zone, using ten bands with MIRI can be detected at 10σ, by observing continuously during two orbital periods. A 5σ detection of spectral features in emission will be

*http://ssc.spitzer.caltech.edu/warmmission/sus/mlist/archive/2013/msg005.txt

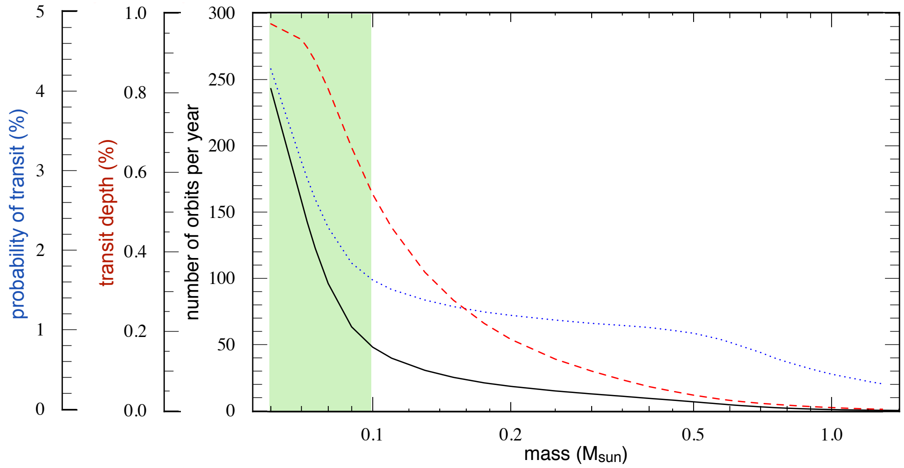

Figure 1: If you like M dwarfs, you'll love brown dwarfs. For a given equilibrium temperature (here 255K, like Earth), the number of orbits (i.e. transits or occultations) per year (black), the transit depth (dashed red), and the probability of transit (dotted blue) as a function of the primary's mass. The green area is where we plan our survey. Stellar parameters were obtained from a 1 Gyr isochrone (Baraffe et al. 1998). The natural evolution of stars and brown dwarfs will alter those curves with time; for brown dwarfs, the rising slopes get steeper.

reached in just 50 occultations (within a year)[1]. This jump in sensitivity is primarily caused by the fast occurrence of occultations, thanks to short habitable orbital periods (see also Belu et al. (2013)).

We will not enter here into considerations about habitability nor about the chemical and photo-chemical processes leading to the eventual emergence of observables biomarkers in a planet's spectrum. We simply note that any discovered planet will become a prime laboratory to study exo-atmospheres and will form a benchmark against which any future mission will refer itself too. *Planets transiting brown dwarfs offer the fastest and most convenient route to the detection and to the study of the atmospheres of terrestrial extrasolar planets.*

the existence of planets orbiting brown dwarfs

Searching for planets around brown dwarfs is close to virgin territory. We can nevertheless build on a few discoveries to extrapolate to this new region of parameter space. The MEarth project found a 6.6 M_{earth} planet transiting a 0.16 $M_\odot$ star (Charbonneau et al. 2009). There are two microlensing events on low mass stars reported in the literature including one caused by a 3.2 M_{earth} orbiting a primary at the limit between stars and brown dwarfs with a mass of only 0.084 $M_\odot$ (Kubas et al. 2012). Accounting for their low probabilities, such detections indicate the presence of a large, mostly untapped, population of low mass planets around very low mass stars (see also Dressing & Charbonneau (2013)). Arguably the most compelling discovery is that of the *Kepler* Object of Interest 961, a 0.13 $M_\odot$ star, orbited by a 0.7, a 0.8 and a 0.6 R_{earth} on periods shorter than two days (Muirhead et al. 2012). The KOI-961 system, remarkably, appears like a scaled-up version of the Jovian satellite system. This is precisely what we are looking for.

Disks around brown dwarfs can be relatively large (> 10 AU), massive and long-lived, providing in principle sufficient mass for the formation of gas giants (eg. Scholz et al. (2008)). While models show gas giants are not expected, smaller mass planets are (Payne & Lodato 2007). Planet formation models also indicate the existence of "bottlenecks" to growth due to dynamical and hydrodynamical processes. This leads to a pile-up of "planetary embryos" with typical masses of order 1 M_{mars} (0.1 M_{earth}) (Kokubo & Ida 2002). Those embryos form the building blocks of larger rocky planets such as Earth. Our survey is meant to be able to detect such small planets. While being able to detect Mars-sized objects may increase our chance of detecting any system around brown dwarfs, their presence, or their absence, will have a direct feedback on the planet formation models themselves.

detecting rocky planets transiting brown dwarfs

Our aim is to be able to detect a single transit event. Observations carried out on *Spitzer* during Cycle 8 (e.g. Heinze et al. (2013)) have shown that whereas photon noise is slightly better in channel 1 at [3.6 μm] than at [4.5 μm], the amplitude of the intra-pixel variability and the number of systematics are smaller in the latter. We simulated a Mars-sized transit event by inserting the signal we seek on real archival *Spitzer* data of a typical brown dwarf within our sample (a J=13.7, L3 dwarf). The study of those simulations indicates that variability in channel 1 can sometimes hide a transit signal, or produce features that can be confused for transits. A single transit detection of a Mars-sized planet cannot be secured when observing at [3.6 μm]. This motivates our choice in favor of channel 2 where similar simulations showed we can distinguish a single planet's signal unambiguously (see Fig. 2).

We used the number of dwarf stars as red, or redder than KOI-961 observed by *Kepler* to infer that ~ 40% of objects have a planetary system with short orbits[2]. Placing a planet on a 30 hour orbit (KOI-961b), it has a 4% probability to transit. Those simple numbers indicate that to obtain two detections, it is required to observe 120 targets for 30 hours continuously, a program close to 4,000 hours of effective observations and overheads. More detailed simulations revealed that a minimum of 5,400 hours of *Spitzer* time is necessary to yield a 90% probability of finding one or more transiting systems. Our most pessimistic case gives a 60% chance of success, while our most optimistic predicts a 10% probability to discover 10 or more systems (with the chance of each containing several planets).

As described, our survey is limited only by *Spitzer*'s observing time and not by the availability of bright-enough brown dwarfs. It can be extended beyond 5,400 hours in the future, to increase the probability of a detection.

[1] simulation only realized for MIRI, but NIRISS, NIRcam and NIRSpec, also onboard *JWST* can study the atmospheres of the planets we will find.

[2] A *Kepler* GO proposal focusing on 1200 late M dwarfs (PI Demory) will soon confirm this occurrence of planetary systems close to the brown dwarf range

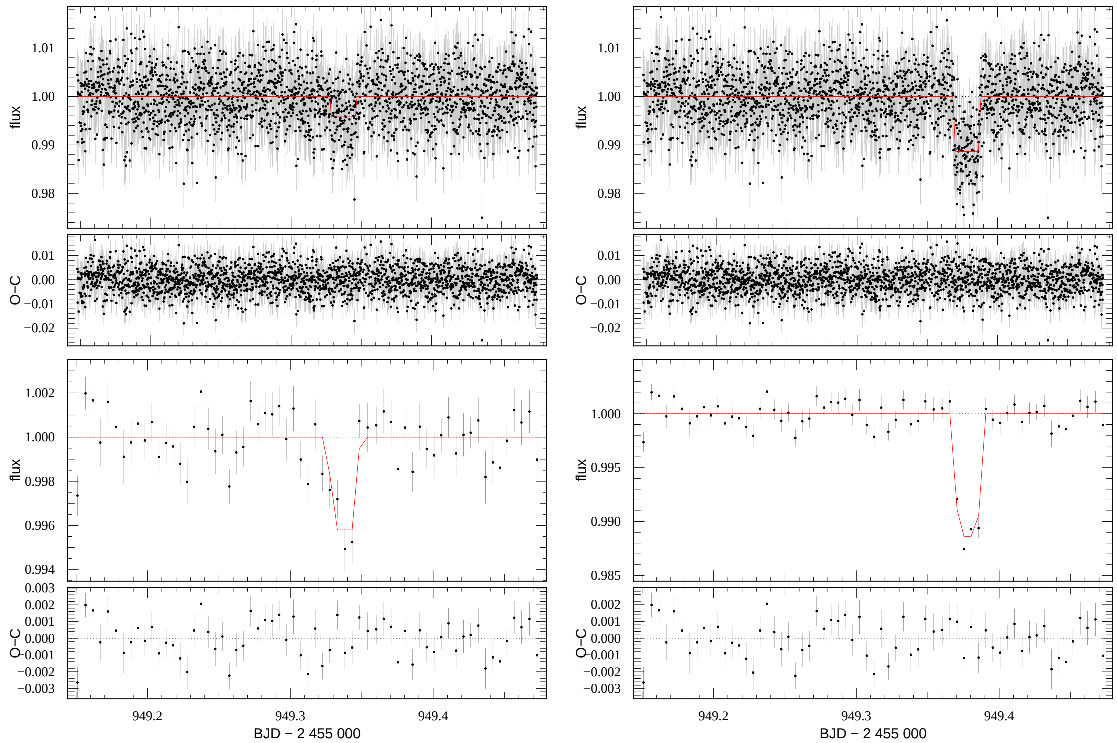

Figure 2: **top** archival *Warm Spitzer* [4.5 μm] data superposed with a simulated transit. We fitted a transit model and included corrections for systematics (notably intra-pixel variations). **bottom** data and model have been binned for visual clarity. **left** a 1 R_{mars} planet transiting a 0.9 R_{Jup} object (Triaud et al. 2013). **right**, a 1 R_{earth}. The transits are located at different times. The residuals (O-C) are similar, illustrating our ability to correct known systematics, distinguish the signal and not over-fit.

summary

The recent selection of *TESS* by NASA testifies to the intense interest in the discovery of nearby transiting planets whose atmospheres can be more readily studied. By surveying brown dwarfs, *Spitzer* has a chance of finding even more favorable objects for atmospheric spectroscopy. Certainly, there are uncertainties regarding planets orbiting brown dwarfs and their possible habitability, that do not exist to the same degree for normal stars. Yet, past exoplanet discoveries have taught us that we should observe without too much theoretical prejudice. Our program will also open the door to the study of planet formation processes at the very bottom of the main sequence.

Spitzer is the only facility that can survey a sufficient number of brown dwarfs, long enough, with the precision and the stability required to credibly be able to detect rocky planets down to the size of Mars, in time for *JWST*. We estimate that about 8 months of observations would be needed to complete the survey[3]. Once candidates are detected, large ground-based facilities will confirm the transits, find the period (if only one event was captured by *Spitzer*) and check for the presence of additional companions. This program will rapidly advance the search for potentially habitable planets in the solar neighborhood and transmit to *JWST* a handful of characterizable rocky planet atmospheres.

Because of the wide interest in the discovery of a nearby transiting Earth-like planet, and the time pressure to identify such targets in time for *JWST* observations, we advocate for publicizing the survey data immediately and thereby allowing anyone to become involved. We also anticipate that the variability data will be of great interest to the brown dwarf community.

References

Baraffe, I., Chabrier, G., Allard, F., & Hauschildt, P. H. 1998, A&A, 337, 403
Belu, A. R., Selsis, F., Morales, J.-C., et al. 2011, A&A, 525, A83
Belu, A. R., Selsis, F., Raymond, S. N., et al. 2013, ArXiv e-prints
Charbonneau, D., Berta, Z. K., Irwin, J., et al. 2009, Nature, 462, 891
Dressing, C. D. & Charbonneau, D. 2013, ArXiv e-prints
Gillon, M., Triaud, A. H. M. J., Jehin, E., et al. 2013, ArXiv e-prints
Heinze, A. N., Metchev, S., Apai, D., et al. 2013, ArXiv e-prints
Kokubo, E. & Ida, S. 2002, ApJ, 581, 666
Kubas, D., Beaulieu, J. P., Bennett, D. P., et al. 2012, A&A, 540, A78
Luhman, K. L. 2013, ArXiv e-prints
Maurin, A. S., Selsis, F., Hersant, F., & Belu, A. 2012, A&A, 538, A95
Muirhead, P. S., Johnson, J. A., Apps, K., et al. 2012, ApJ, 747, 144
Payne, M. J. & Lodato, G. 2007, MNRAS, 381, 1597
Scholz, A., Jayawardhana, R., Wood, K., et al. 2008, ApJL, 681, L29
Seager, S. & Deming, D. 2010, ARA&A, 48, 631
Selsis, F., Wordsworth, R. D., & Forget, F. 2011, A&A, 532, A1
Triaud, A. H. M. J., Hebb, L., Anderson, D. R., et al. 2013, A&A, 549, A18

[3]Scheduling constraints would be minimal since any system can be targeted at any time; the observing load could be spread over several cycles. Thanks to the intrinsic faintness of our targets, it is also a program requiring low volumes of downlink.